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This report is submitted in completion of the ONR Special Research Award in Ocean Acoustics: Entry-Level Faculty Award.

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Title: Environmental complexity and stochastic modeling of high frequency acoustic scattering from the seafloor

Principal Investigator:

Christopher D. Jones
Applied Physics Laboratory
University of Washington
1013 NE 40th Street
Seattle, WA 98105-6698
Tel: 206-543-1615, FAX: 206-543-6785
Email: cjones@apl.washington.edu

ABSTRACT

Models of acoustic scattering from the seafloor generally assume that sediment heterogeneity is statistically homogeneous with single-scale correlation structure. Current statistical descriptions of the seafloor are incapable of capturing information about complex seafloor heterogeneities that are often encountered in marine environments (e.g. non-uniform or clustered scatterers, patchiness in the sediment physical properties). Seafloor complexity is due to a variety of processes including bioturbation (burrows, fish pock marks), biogenic deposits (shell lags), hydrodynamics factors (ripples), and geological processes that create stratification and non-uniform deposition (flaser bedding), for example. An overly simplified description of the seafloor will lead to errors in acoustic model predictions, uncertainty in interpreting measurements of acoustic scattering, and unreliable inversions for environmental parameters. This investigation addresses the effects of complex and non-Gaussian seafloor heterogeneity on scattering. A combination of numerical modeling, stochastic process modeling, and field data analysis are employed to investigate the errors and uncertainty associated with using incomplete models of seafloor randomness.

LONG-TERM GOALS

The long-term goal of this work is to develop statistical models of high frequency scattering from complex and realistic seafloor environments. Better statistical descriptions of scattering from complex environments will improve forward model predictions of seafloor scattering in realistic scenarios and enable the solutions to interesting inverse problems related to sediment biological, hydrodynamic, and geological processes.

OBJECTIVES

The short-term objectives are: 1) to address the accuracy of current methods of modeling scattering from the seafloor in environments where the sediments have complex heterogeneity; and 2) to apply new stochastic methods of describing complex scattering and random structures in the sediment to improve models of seafloor scattering.

APPROACH

Stochastic Modeling:

Towards the goal of using acoustic scattering as a tool to study temporal variability in benthic processes, the first part of this project is based on the use of correlation methods to observe seafloor change. From a measurement perspective the problem may be viewed as making phase coherent vs. phase incoherent estimates of scattering. Scattering intensity or scattering strength is an *incoherent* measure of scatter derived from the magnitude of the scattered signal at a single point in time. In the context of Born scattering, the scattering strength is proportional to the spectrum of the fluctuations in the medium, which is typically not a sensitive measure of seafloor change as the spectrum by definition remains constant from realization to realization. A *coherent* measure of scatter is the temporal cross-correlation of seafloor scattering. Correlation methods are typically more sensitive to change as both amplitude and phase relations are preserved, and phase is a sensitive measure of change in the medium.

Alternatively, a probabilistic approach is pursued along the same lines of reasoning as theoretical descriptions by [McDaniel, J. Acoust. Soc., **88**(3), September 1990] and in backscatter data analysis by [Lyons, J. Acoust. Soc., **106**(3), September 1999]. The work shows interesting non-Rayleigh characteristics of backscatter amplitude associated with several bottom descriptions (i.e. patchiness). The implication here is that patchiness in the bottom will reveal itself in backscatter through fluctuation statistics. However, in previous studies there was no attempt to address the physical mechanisms of the observed and predicted behavior by simulations. The scattering model assumptions used by McDaniel are unnecessarily restrictive (i.e. delta correlated scattering kernel) to allow broader interpretation and extension to more current models of seafloor scattering.

Numerical Modeling:

Numerical simulation are used to: 1) perform numerical experiments and develop simulated data to gain physical insight into scattering from complex environments; and 2) access the statistical errors and uncertainties associated with using current acoustics models in complex environments. Specifically, simulations will be performed to investigate temporal and spatial variability in scattering associated with complex sediment roughness (non-uniformity and patchiness),

Two-dimensional Monte-Carlo simulations are used to test fundamental modeling assumptions. Three-dimensional simulations are used in a limited number to examine the

effects of horizontal variability and to address issues of uncertainty in realistically complex environments. In both cases simulations are performed with finite-difference-time-domain methods (FDTD). This work was done in collaboration with John Schneider of Washington State University.

In addition to simulating scattering, numerical methods are also used to generate realizations of complex seafloor structures. Numerical point process models and Markov random field models are used to generate realizations of the seafloor that exhibit clustering and non-Gaussian randomness.

Experiments/Measurements:

No new field experiments are presented in this investigation. However, field measurements from existing experiments (FHL-PAL, DRI) are used.

WORK COMPLETED

1. Temporal Variability of scattering:

Figure 1 illustrates the normalized backscatter decorrelation (1-correlation) for different sites in which observations were made over a period of a month (at 40 kHz) in a variety of shallow-water environments and sediment types. The decorrelation in time of the backscattered field shows characteristic decay rates that are most likely a function of the different types and rates of biological activity associated with each environment. In contrast (but not shown), the scattering strength measurements at these same sites do not show such distinct characteristics that can be associated with the sediment type and the dominant scattering mechanism.

Acoustic backscatter can provide a means of sensing biological processes at spatial and temporal scales that are larger than current point sampling methods. However, at the frequencies of interest in this paper scattering is an *indirect* measure of activity, providing a statistical measure of the net randomizing effects of the activity on the sediment bulk properties. If the acoustic wavelength is comparable in scale to the scales of sediment organisms (i.e. burrow size), acoustic imagery will not provide information about individual organisms. Rather, in conjunction with direct sampling and better models of the mechanisms of biological alteration of sediment, scattering can potentially provide a tool for forward and inverse problems dealing with biological processes.

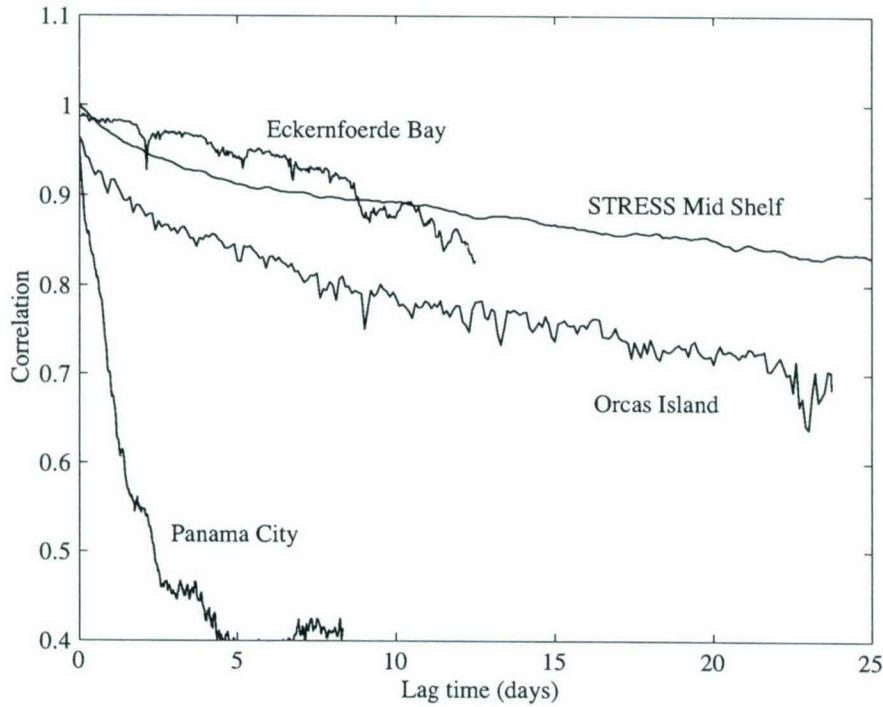


Fig.1: Temporal decorrelation of seafloor backscatter at various site.

The temporal correlation of the backscattered field is found by correlating collocated returns from the seafloor as a function of transmission time. Consider the monostatic geometry for backscatter as illustrated in Figure 2 where a source/receive system is fixed in space and measures backscatter at discrete pulse transmission times τ_n . The temporal correlation of backscatter signals between a transmission at time τ_m and a later transmission at τ_n is defined as

$$C(\mathbf{r}; \tau_m, \tau_n) = \langle u(\mathbf{r}; \tau_m) u^*(\mathbf{r}; \tau_n) \rangle, \quad (1)$$

where $u(\mathbf{r}; \tau_n)$ is the complex envelope of the backscattered field as a function of range \mathbf{r} along the seafloor. For $m = n$ the correlation function is real and proportional to the signal intensity. With $m \neq n$ and if the seafloor has changed, the correlation function will be complex due to signal phase fluctuations primarily. With $m = 0$ as the reference time and $n = 1, 2, 3, \dots$ increasing monotonically, equation (1) is the *cumulative* temporal correlation function.

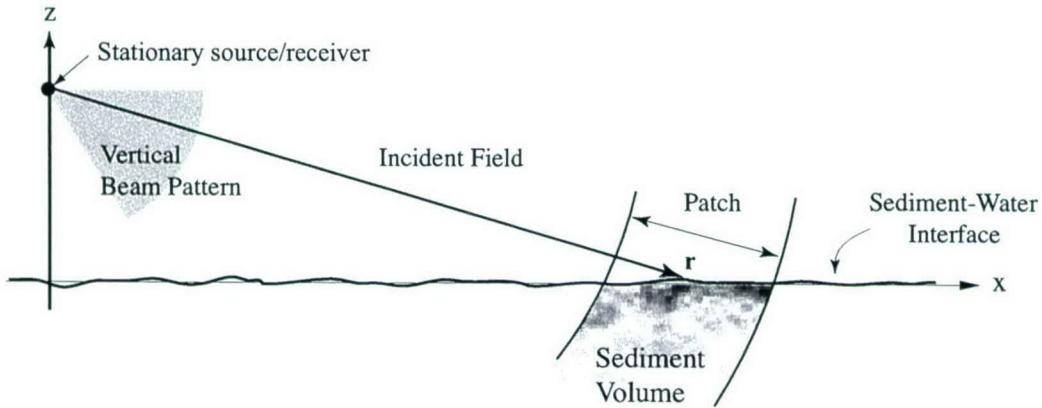


Fig.2: Geometry of the bottom backscattered patch.

The size of the area of seafloor (or patch) used to estimate the correlation is defined by the length of the transmitted pulse and the number of samples needed to form an accurate estimate. For a signal of bandwidth-limited Gaussian signal with bandwidth B , the normalized mean-square error of the correlation estimate is given as

$$\varepsilon^2[\hat{C}(\mathbf{r}; \tau_0, \tau_n)] = \frac{1}{2BT} [1 + \rho^{-2}(\mathbf{r}; \tau_0, \tau_n)(1 + N/S)^2], \quad (2)$$

where ρ is the desired true correlation coefficient and T is the length of the record used to form the estimate (corresponding to the number of points M or patch size). The ratio S/N is the signal to noise ratio assuming the noise level is constant and uncorrelated between transmission times τ_0 and τ_n .

1.1 Example of benthic biological activity (new data analysis):

Benthic biological activity creates variability in the seafloor by reworking sediment microtopography and volume heterogeneity (e.g. epifaunal and infaunal deposit feeding). The effects of biota on sediment structure are typically studied using sediment cores and optical imagery. Cores, including high resolution x-radiographs and CT scans, provide direct sampling of the vertical and small scale horizontal structure (less than a meter) of sediments at an instant in time and for a single horizontal location. Non-destructive in-situ methods, such as video and stereo photography, provide better temporal resolution with less impact on the sediment. However, they are also limited to small spatial scales and only provide information about the visible sediment interface.

Making observations of scattering with direct observations of isolated biological processes is a step towards this goal. An example of observed biological activity with backscatter decorrelation is illustrated in recent experiments at the Friday Harbor Laboratories on San Juan Island, Washington. In these field experiments, sand patches were created over mud sediment and burrowing shrimp were introduced to create mixing of the stratified sediments. Figure 3 illustrates the backscatter strength and the cumulative decorrelation intensity over a semicircular area of seafloor created by scanning a narrow beam 120 kHz transducer, similar in geometry to Figure 2. The two areas of higher relative cumulative decorrelation (indicated by circles) are the sand patches approximately one day after the burrowing shrimp were introduced. Decorrelation is attributed to increase burrowing and mixing of the sand. In contrast, the intensity of the active areas is similar to the background mud sediments. Figure 4 illustrates the average strength and cumulative decorrelation within the two patches and the background as a function of time after introducing the shrimp. Rapid decorrelation is observed within the first several days of the shrimp manipulations. At approximately 8 days after the manipulations, the scattering strength of the patches increases. In contrast, the cumulative decorrelation during this period (relative to a new initial scan at day 8) shows reduced activity compared to the initial placement of the shrimp. An explanation of this observed rise in scattering strength (although small) is difficult; however it illustrates the potential differences in the two types of measurements (coherent vs. incoherent).

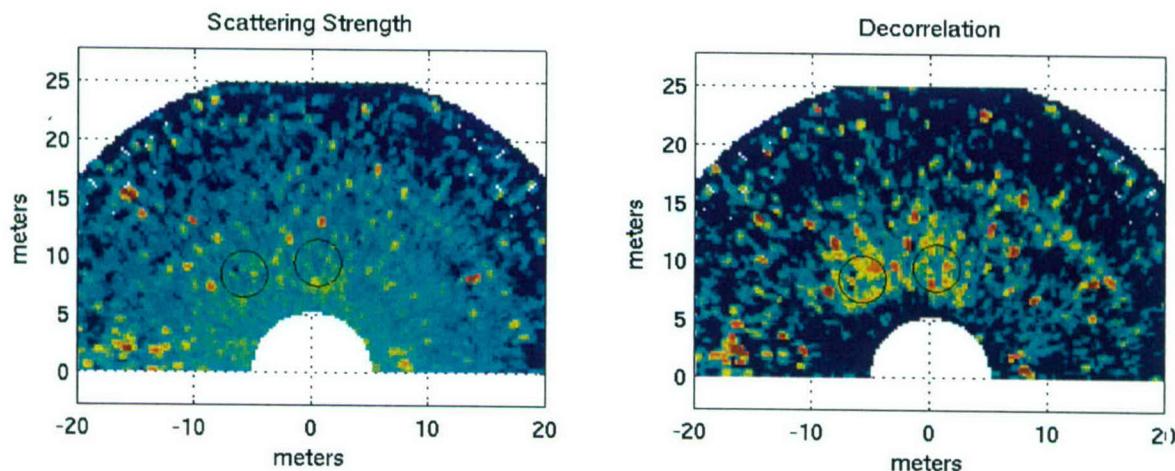


Fig.3: Image of seafloor backscatter intensity and cumulative decorrelation showing areas of sand as compared to mud sediment

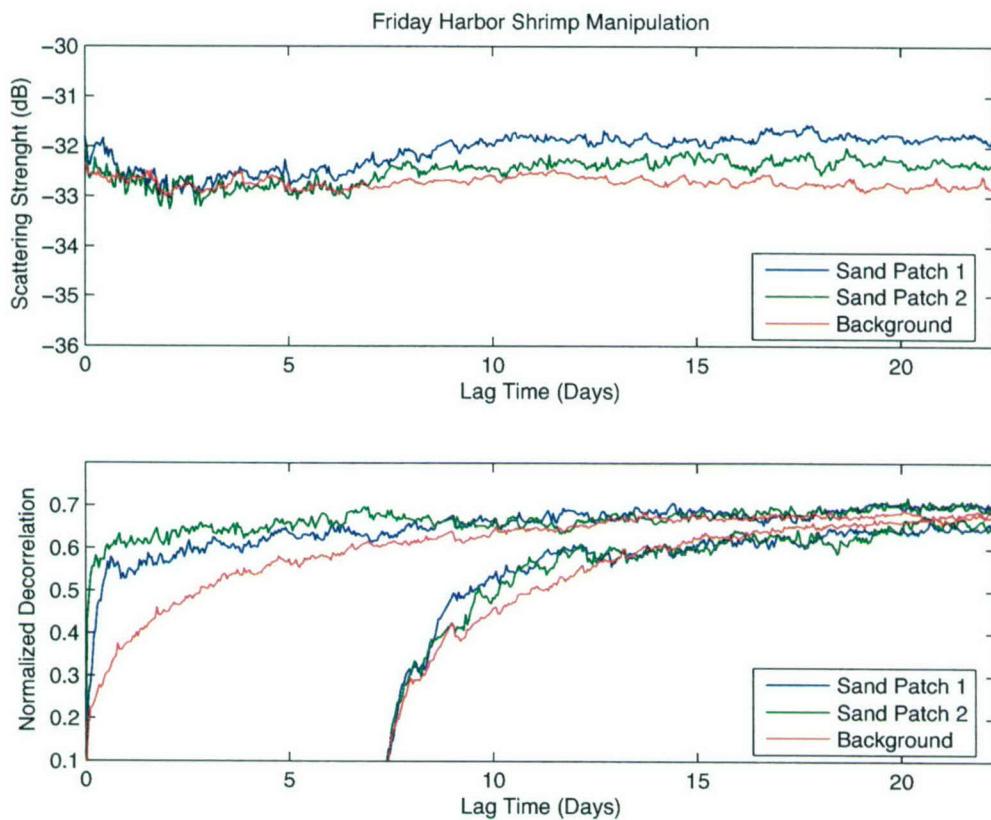


Fig.4: Time evolution of backscatter strength and cumulative temporal decorrelation of sand patches with burrowing shrimp as compared to nearby mud sediment.

2. Fluctuation Statistics:

Scatter from the seafloor is simulated in the time domain to develop statistical descriptions of backscatter as a function of different bottom types. Figure 5 illustrates the simulation geometry and provides an example of the backscattered signal as a function of time when a pulse travels along the seafloor at an oblique angle of incidence. Time domain simulations are performed using FDTD methods in 2-D. 3-D capabilities have been developed but not used in this study to date.

To develop envelope fluctuation statistics, multiple realizations of the bottom are generated and simulations are performed for each realization. As illustrative examples of the different and sometimes ambiguous *detection probabilities* (1-CDF) associated with different bottom descriptions, two cases are shown (Figures 7-10).

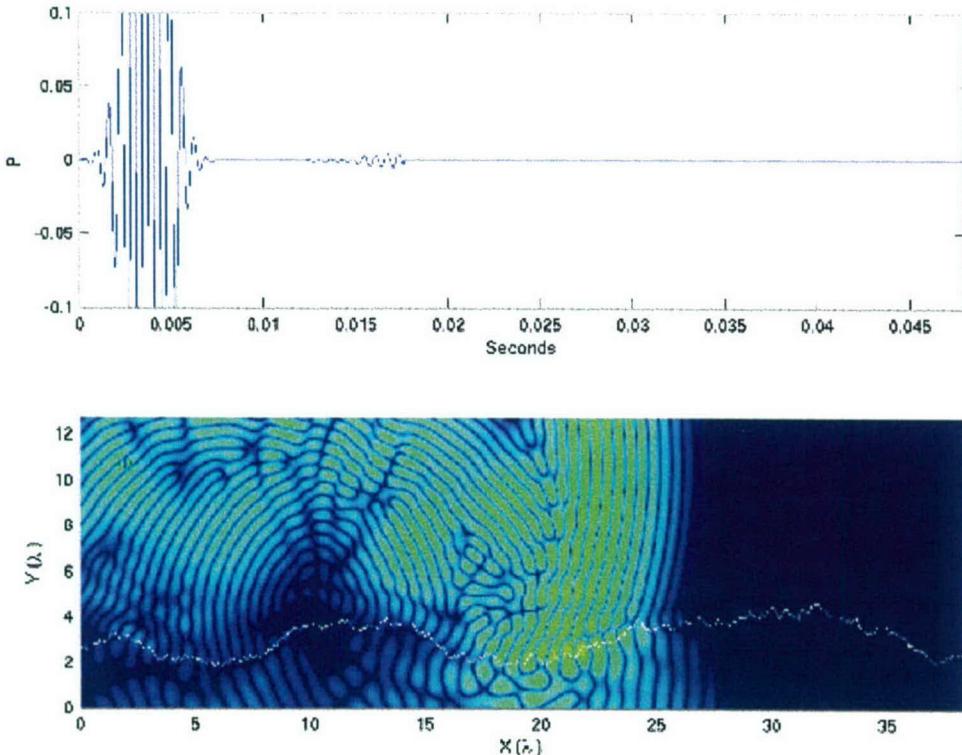


Fig 5: Time domain simulation of scattering of a pulse from the seafloor showing a pulse backscatter (top panel) and scattered field in the medium (bottom panel).

The first case with the seafloor is described by a hypothetical two-scale statistical model. Figure 6 illustrates a single realization of a rough surface for the case where a Gaussian spectrum is superimposed over a power-law spectrum. The power-law surface (F1) describes the high wavenumber roughness on the bottom, where the Gaussian surface (F2) captures the larger scale fluctuations in bottom topography. Figure 7 shows the associated detection probabilities at various grazing angles of the backscattered field using 50 realizations of the two-scale model.

Figure 8 illustrates another realization of the seafloor described by an alternative two-scale statistical model. In this case a Gaussian surface is convolved with a power-law spectrum. Again, the power-law surface (F1) describes the high wavenumber roughness on the bottom, where the Gaussian surface (F2) captures the larger scale fluctuations in bottom topography. The convolution of the two surface descriptions is merely an analytic tool for describing a complex seafloor. Figure 9 shows the associated detection probabilities at various grazing angles of the backscattered field using 50 realizations of the two-scale model.

In both cases these examples illustrate the effects of patchiness and the complexity that is observed in realistic seafloor description. And in both cases, significant non-Rayleigh statistics are observed at low grazing angles.

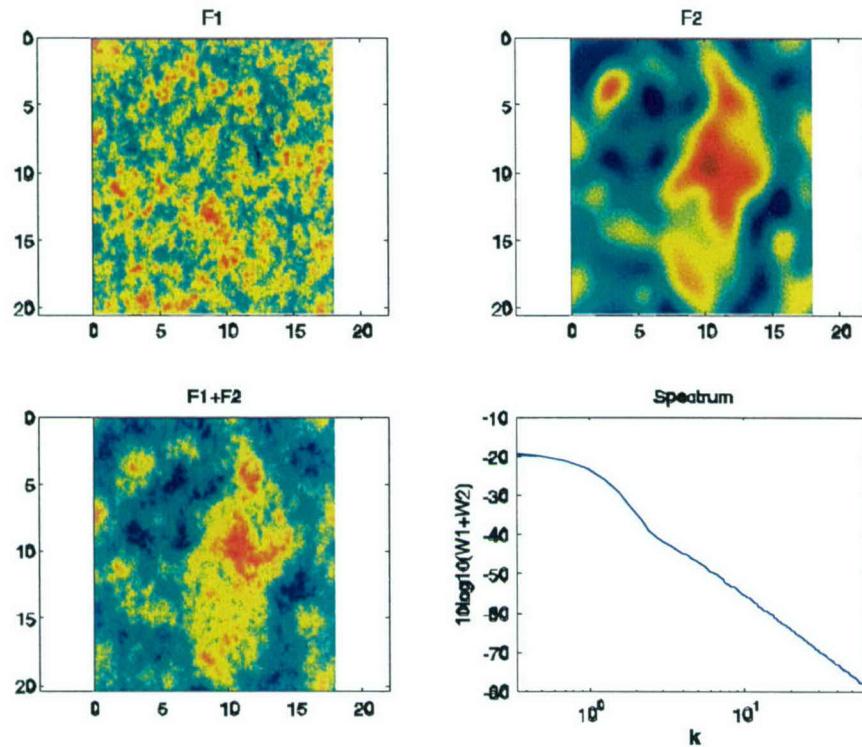


Fig 7: Two scale rough surface model. $\text{RMS_rough1}=1/4$; $\text{RMS_rough2}=2/3$; $\text{Lc_rough1}=1$; $\text{Lc_rough2}=3$. All dimensions normalized by wavelength in water.

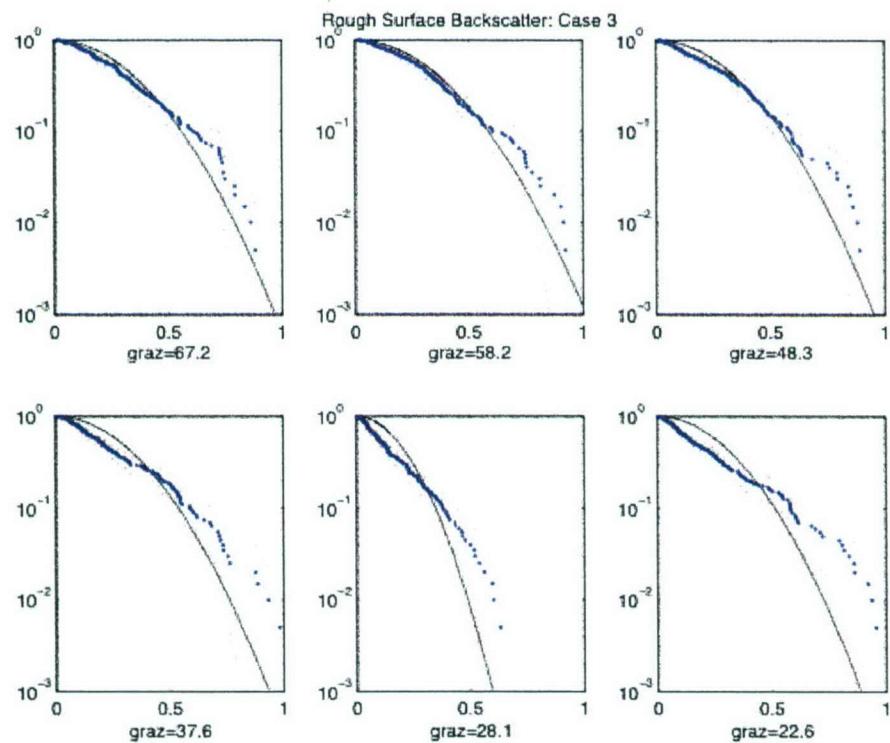


Fig 8: Backscatter detection probabilities at various grazing angles for the two-scale seafloor roughness $F1+F2$.

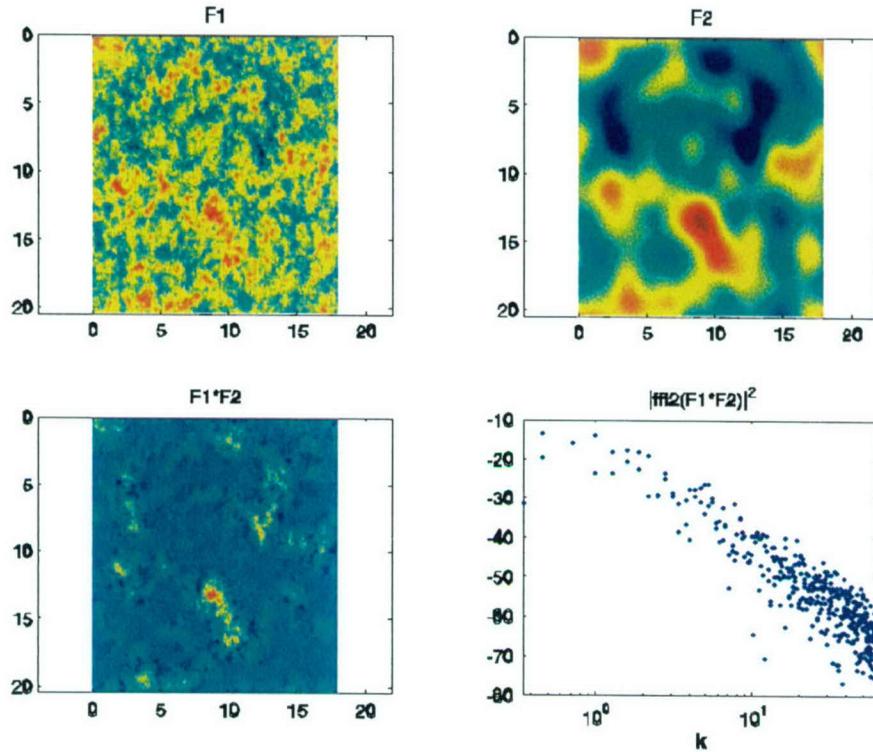


Fig 9: Two scale rough surface model $F1*F2$. $RMS_rough1=1/4$; $RMS_rough2=2/3$; $Lc_rough1=1$; $Lc_rough2=3$. All dimensions normalized by wavelength in water.

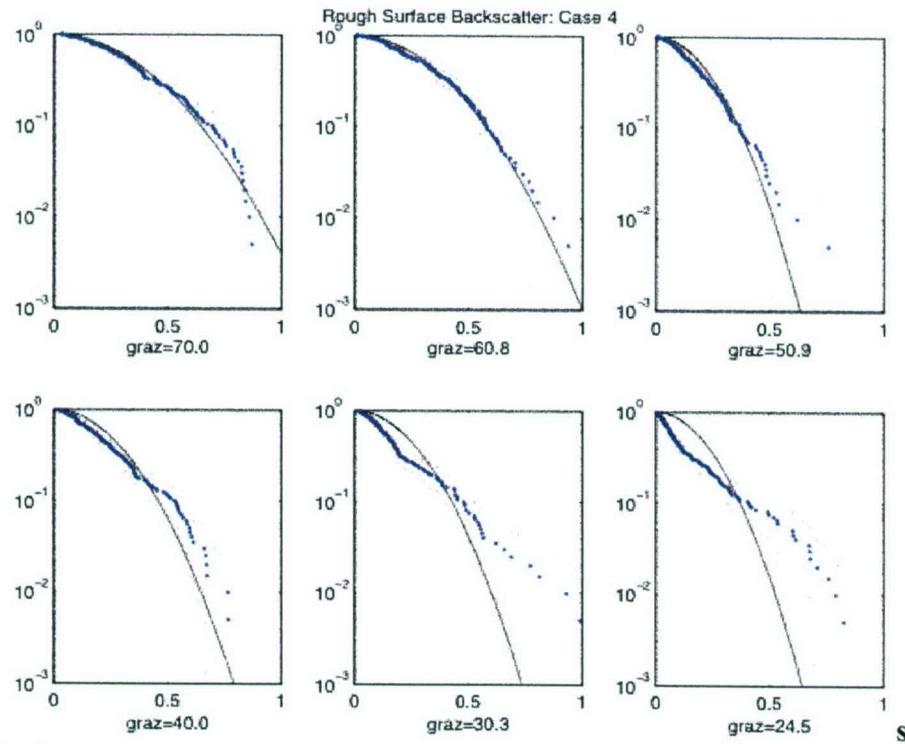


Fig 10: Backscatter detection probabilities at various grazing angles for the two-scale seafloor roughness $F1*F2$.

RESULTS/ PUBLICATIONS

Publications resulting from this award (beyond conference abstracts and papers) are currently being prepared and are not in print as of the completion date.

RELATED PROJECTS

Award Number: N00014-04-1-0044, *High Resolution Stereo Imaging System for Sediment Roughness Characterization.*

IMPACT/APPLICATIONS

The techniques of characterizing the seafloor developed in this effort may have impact and application to studies of biological activity at the seafloor and its effects on high frequency imaging and scattering and methods of detecting and identifying objects and targets at the seafloor.